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Merger of a Neutron Star with a Newtonian Black Hole

by

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ABSTRACT

Newtonian smooth particle hydro simulations are presented of the merger of a 1.4 $M_\odot$ neutron star with a black hole of equal mass. The initial state of the system is modeled with a stiff polytrope orbiting a point mass. Dynamical instability sets in when the orbital separation is equal to about three stellar radii. The ensuing mass transfer occurs on the dynamical timescale. No accretion torus is formed. At the end of the computation a corona of large extent shrouds an apparently stable binary system of a 0.25 $M_\odot$ star orbiting a 2.3 $M_\odot$ black hole.

Key words: *Black hole physics – Stars: neutron – Hydrodynamics*

1. Introduction

Several binary systems are known in which one of the components is a high mass ($M > 3$ $M_\odot$) compact object, *i.e.*, a black hole (bh) candidate. The largest values of the lower limit on the black hole candidate are obtained in low-mass binaries, such as V404 (Casares and Charles 1994), A0620-00 and X-ray Nova Mus (Orosz *et al.* 1994). These systems (Tanaka 1995, van Paradijs and McClintock 1995) usually suffer from X-ray outbursts of distinctive properties. High-mass binaries with a black hole candidate are also known, of which Cyg X-1 is the best known.

It seems natural to expect, that close binaries composed of a black hole primary and a neutron star secondary may be formed in the course of stellar evolution. If such close binaries exists, there is little doubt that because of angular momentum losses to gravitational radiation the orbit will decay, as it does in the Hulse-Taylor type neutron star binaries, until the two components are brought together. Such processes and their supposed products have been discussed in the literature in the context of gamma-ray bursts, for which the merger of a black hole and a neutron star seems to be the currently preferred model (Paczyński 1991, Witt *et al.* 1994).

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4. Binary Merger of Two Polytropes

We have performed a rigorous calibration of our code to the results presented by Rasio and Shapiro 1994 (hereafter RS). RS used a different method of computing gravitational interactions and run simulations with about ten times as many particles as were used by us.

We have successfully reproduced the evolution of a binary system consisting of two identical polytropes (with index $\Gamma = 3$ and initial mass 1.4 $M_\odot$ each) initially placed at a separation which is slightly less than the dynamical stability limit. Following RS, we obtained the initial condition by relaxing the two stars in their mutual potential but maintaining the separation between their centers of mass fixed at $r = 2.95$ in units of the initial unperturbed radius of an (isolated) polytrope. During the relaxation, particle entropies were maintained and oscillations were damped on the dynamical timescale through a term linear in the velocity. The angular velocity of the rotating frame was continuously updated so that the centrifugal and gravitational accelerations at the centers of mass cancel exactly. The period, $P = 2.54$ ms, corresponding to this angular velocity at the end of the relaxation process is taken as the unit of time.

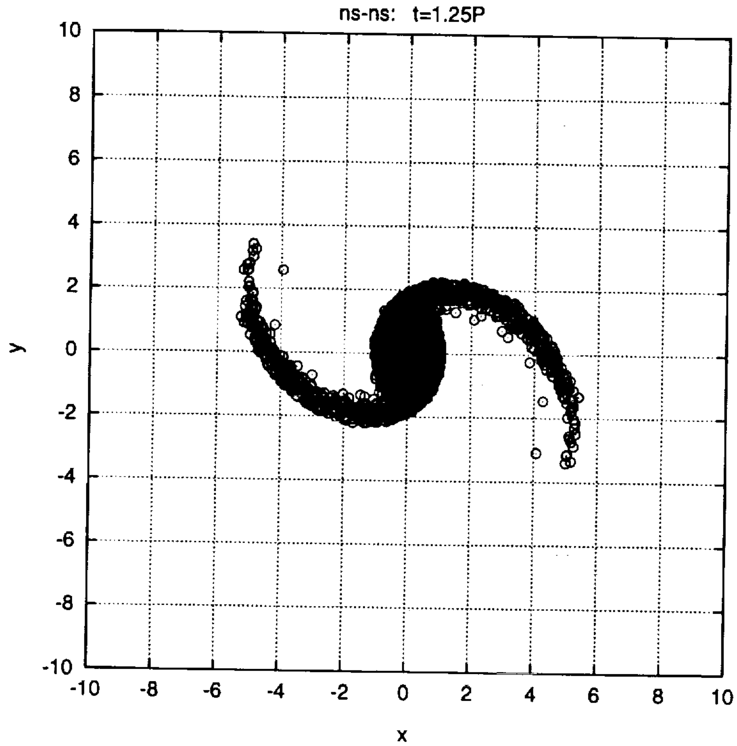
Upon relaxing the polytropes, we removed the artificial constraints while setting the time equal to zero and allowed the system to evolve naturally. We terminated the computation at $t = 3P$. Comparison of our results (Fig. 1) with those of RS (their Fig. 5) illustrates the good agreement between the two sets of results (an offset of our initial time by about $0.75P$ relative to that of RS has to be taken into account).

Although our computation was fully Newtonian, we also present the gravitational radiation amplitudes (dotted line in Fig. 6) computed from the quadrupole formula adapted for SPH as in Rasio and Shapiro, 1992. Agreement with the results of RS is excellent.

5. Merger of a Black Hole with a Polytrope

We have investigated the dynamical stability and the dynamical evolution of a binary system composed of a polytrope and a Newtonian model of a black hole. The initial mass of each of the two components was taken to be equal 1.4 $M_\odot$. Apart from a trivial change of the orbital separation, the procedure for setting up the initial condition of the binary is identical to that described in Section 4, except that one of the polytropes has now been replaced with a Newtonian point mass.

To investigate the evolution of the system we have modeled the black hole by a Newtonian point mass with an absorbing boundary. Specifically, whenever the distance of any particle from the point mass ("black hole") decreases to $r \leq 2GM/c^2$, where M is the current mass of the black hole, that particle is removed from the computational domain. At the same time, the mass and velocity of the black hole are adjusted to assure overall conservation of mass and momentum.



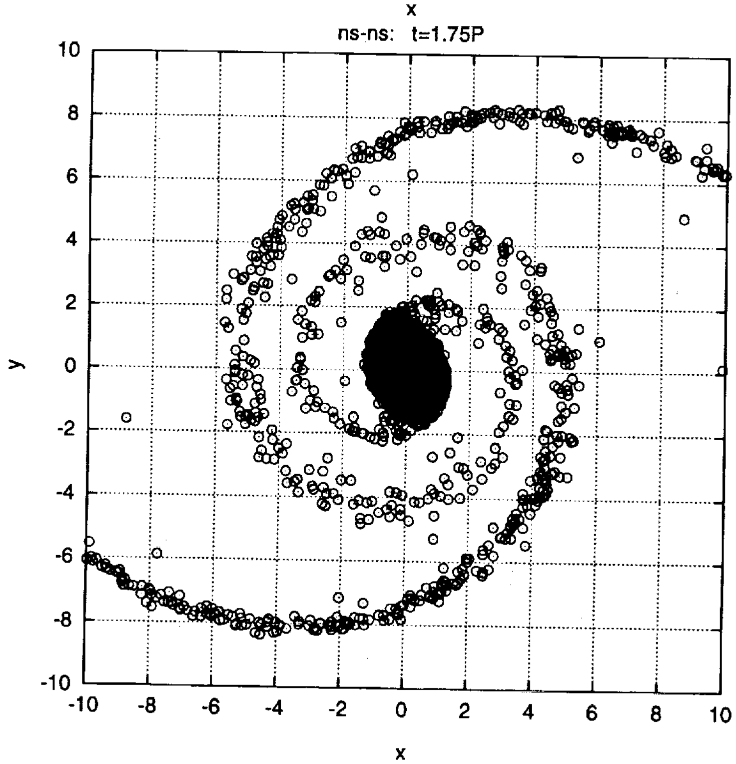
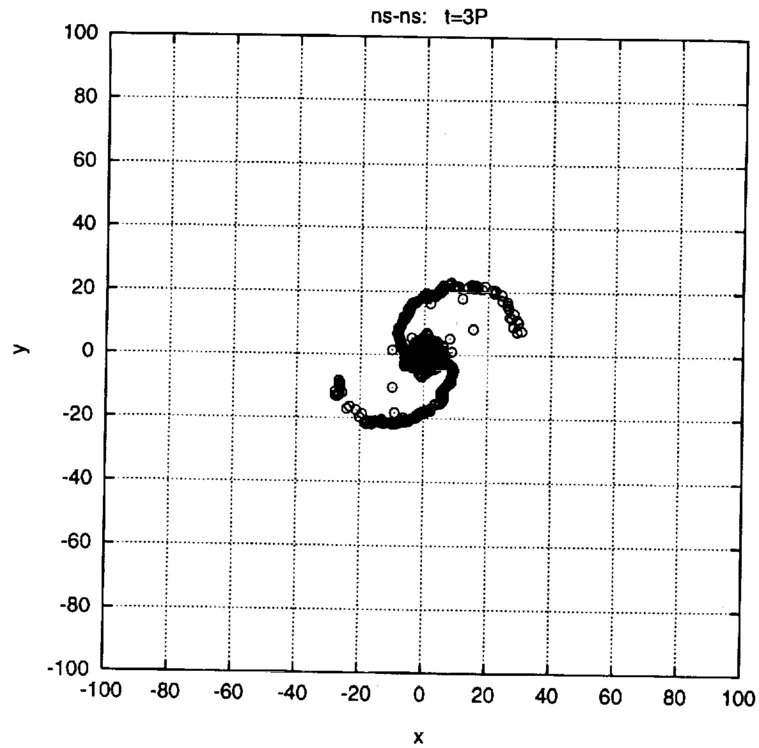


Fig. 1. Concluded.



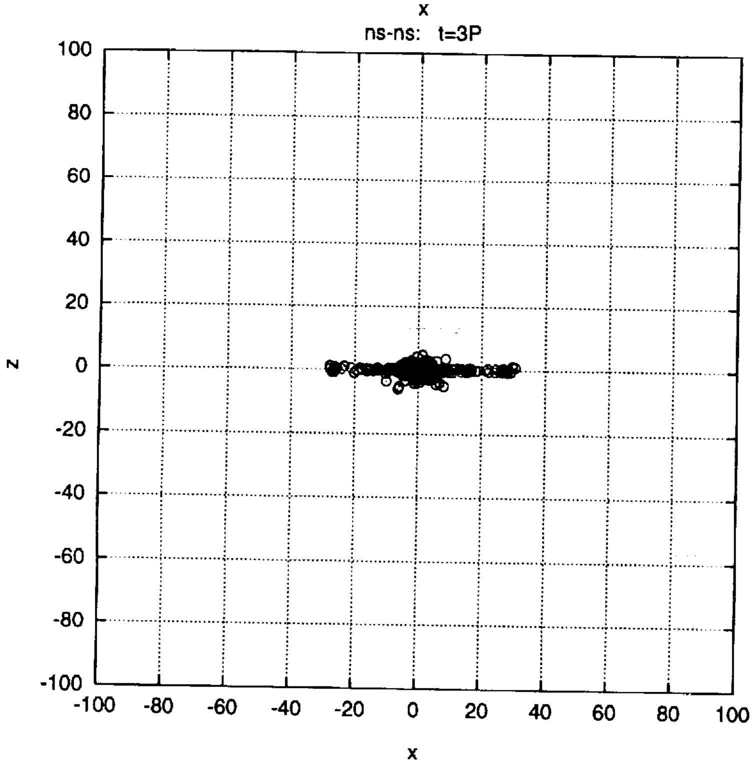


Fig. 2. Large scale view of the merged polytropes. Projections onto the orbital xy plane as well as onto the xz plane are shown.

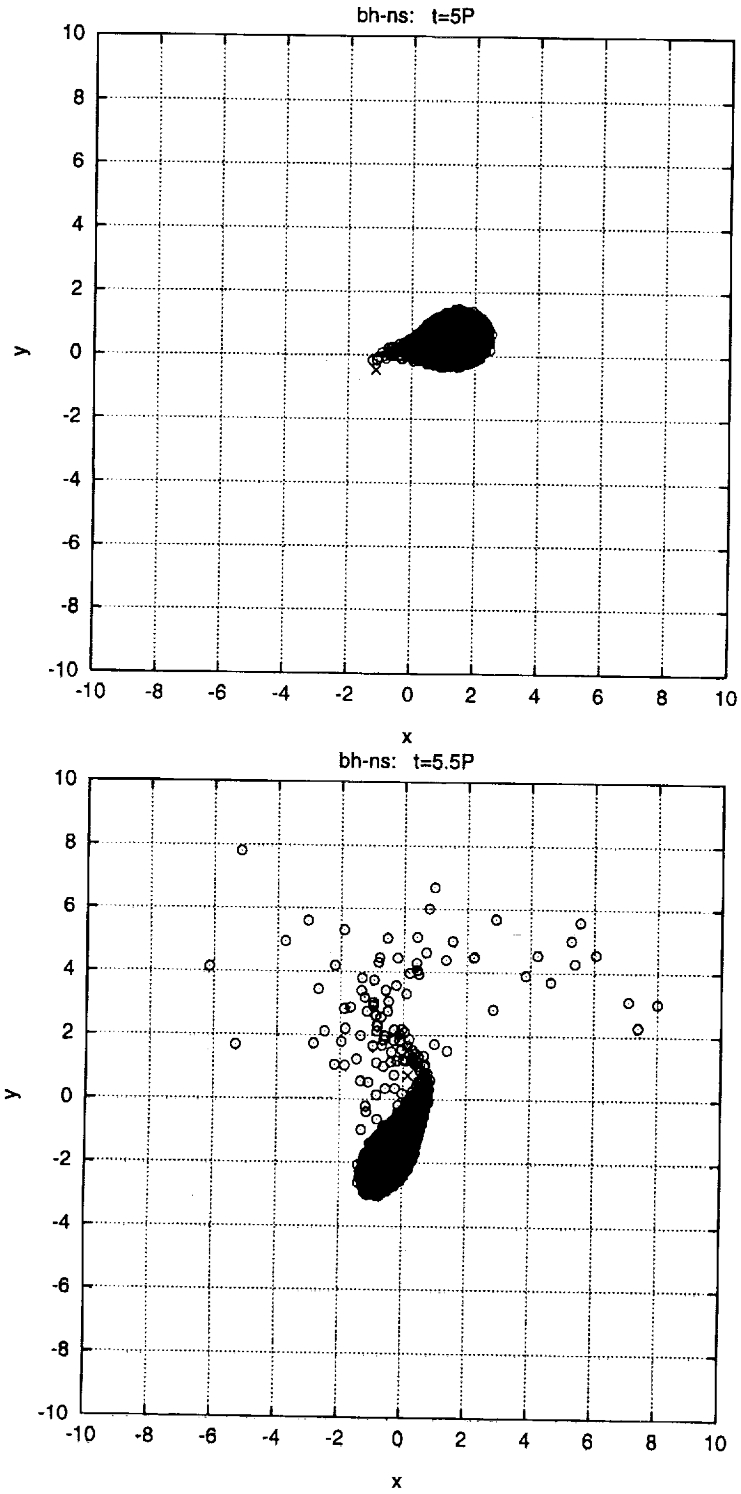
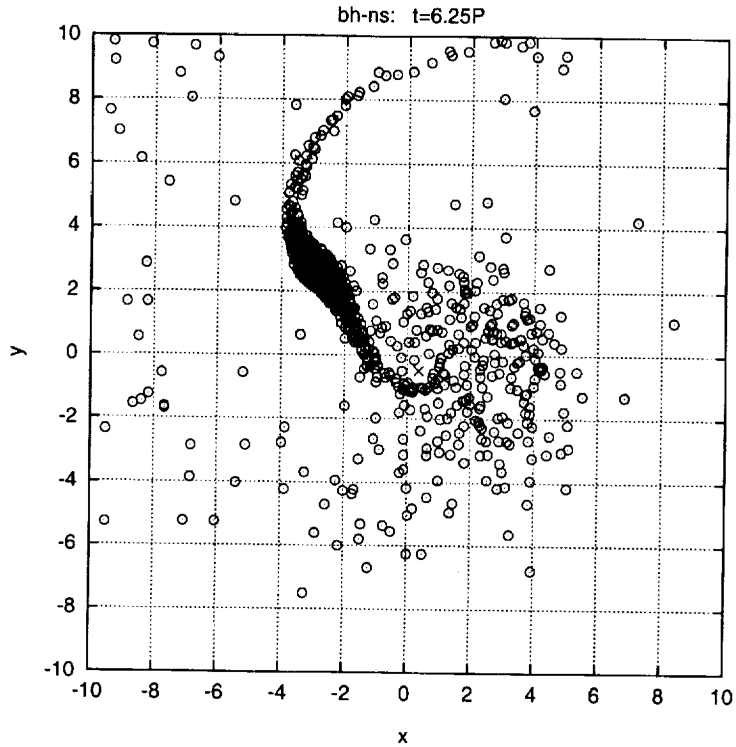
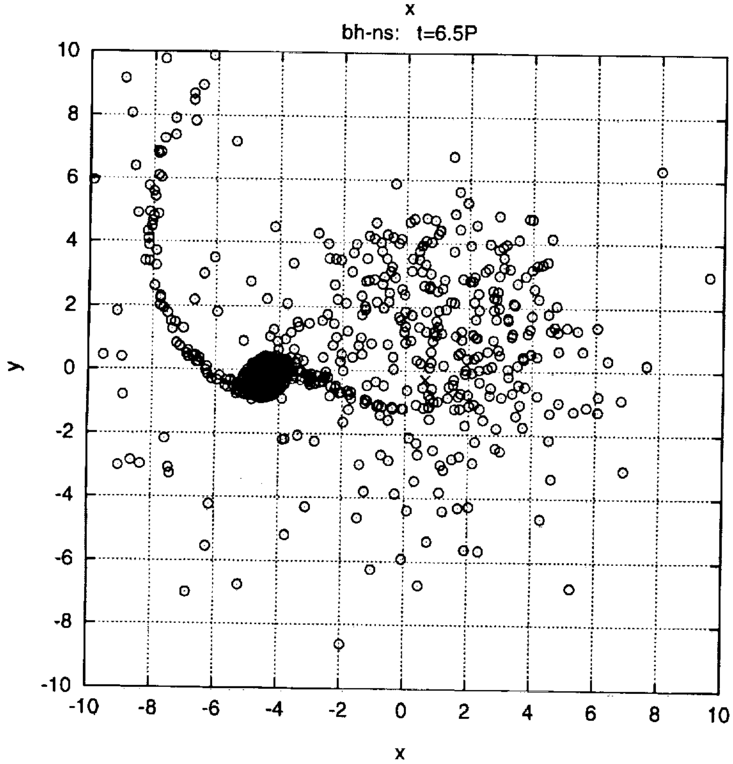


Fig. 3. Continued.





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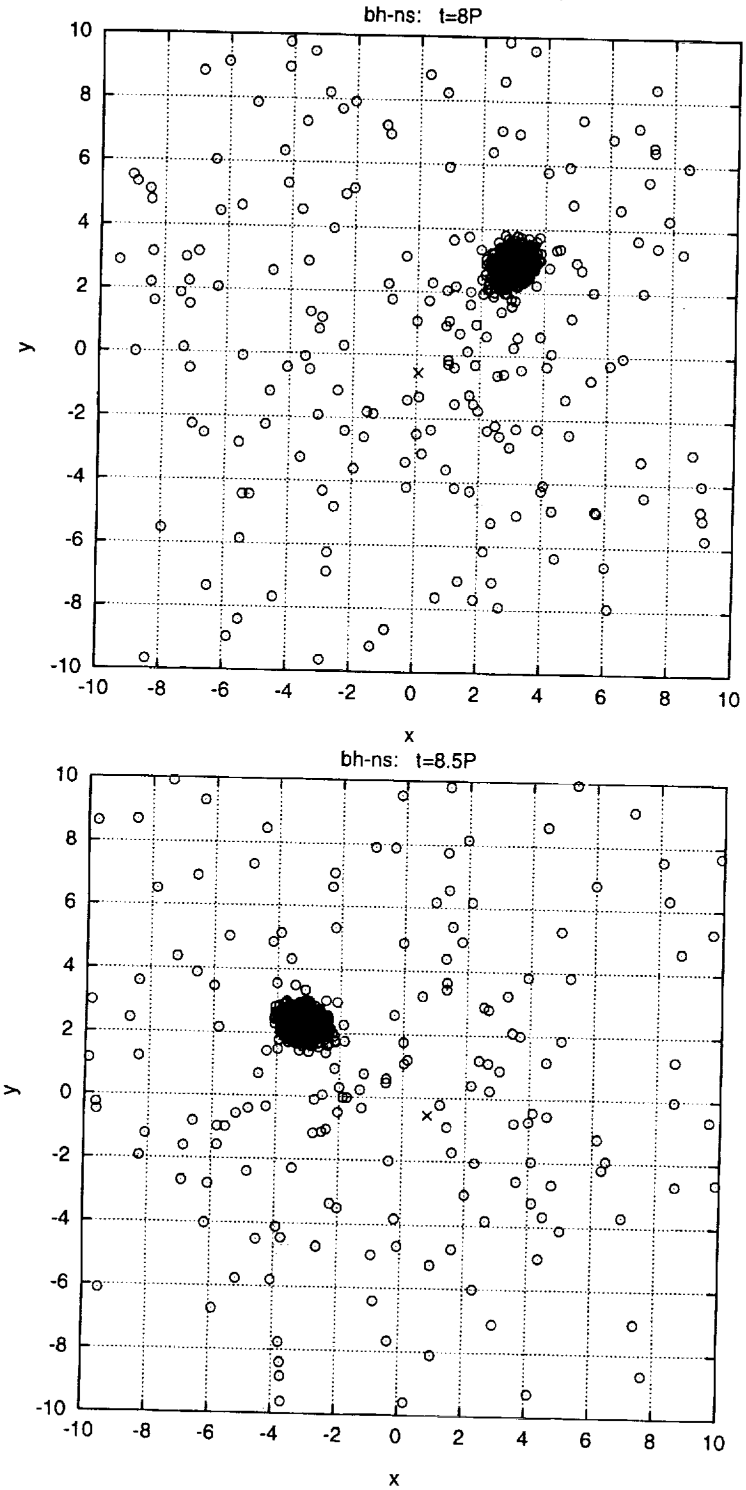

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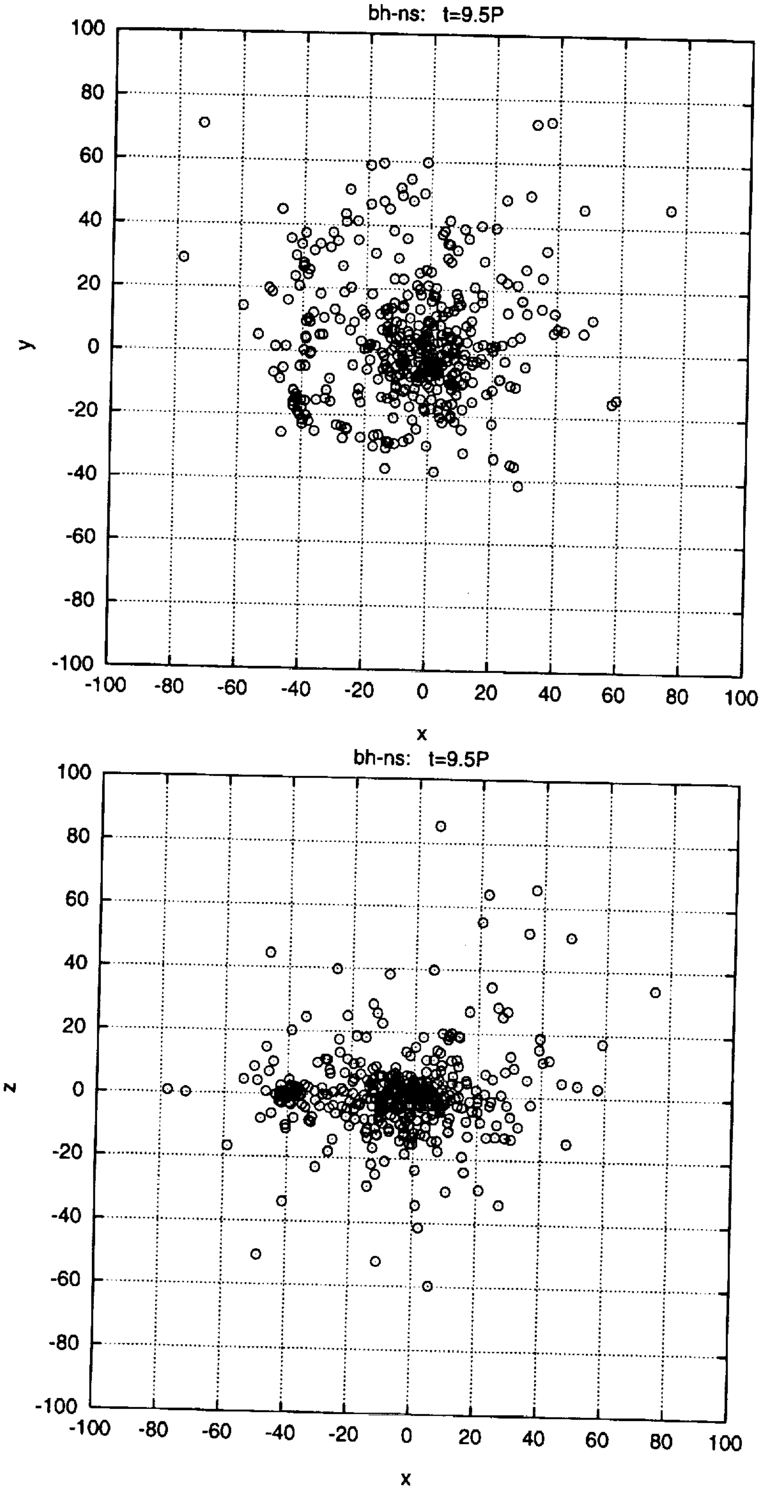

Fig. 4. Large scale view of the black hole system after the end of mass transfer.

star black hole merger is much more rapid, although it occurs with a somewhat larger delay with respect to the onset of the dynamical instability. This leads to a rather different gravitational wave signature of the two events (Fig. 6).

In terms of the morphology of mass distribution, the main difference seems to be connected with the rotational symmetry (by π) in the NS–NS system and its absence in the NS–BH case. This leads to the formation of an $m = 2$ mode spiral pattern in one case, and what could perhaps be called a transient $m = 1$ mode in the other. Further, a comparison of the particle positions projected onto the xz plane reveals that mass ejection is essentially confined to the orbital plane in the NS–NS case but is fairly isotropic (three-dimensional) in the NS–BH case.

In the NS–NS case the binary is destroyed in a complete merger of the two stellar cores. In the NS–BH computation presented here, the dynamical instability is equivalent to a rapid mass transfer episode in which the core of the secondary preserves its identity and the binary survives, albeit with a greatly altered mass ratio.

6.2. *Survival of the Polytropic Core*

The most striking feature in our Newtonian SPH simulation of the dynamical instability in a black hole binary is the survival of the polytropic core and of the binary system itself. It would appear that this is a consequence of momentum conservation in an asymmetric system.

In some sense, the outcome of the dynamical instability seems to be equivalent to the well studied case of (slow) mass transfer in a binary. Note that the deformation of the polytrope is fairly slight in the initial phases of mass transfer and that at the onset of the rapid phase, at $t \approx 5P$, the mass donor is already clearly less massive than the mass acceptor. In conservative evolution of a binary, the orbital separation increases in such a case (*e.g.*, Savonije 1983). Clearly, the dynamical evolution presented in Section 5 is not conservative, and strictly speaking the system is no longer a binary. Mass is lost together with angular momentum and some orbital angular momentum is converted into spin of the black hole – these effects counteract the increase of binary separation. The actual balance between the competing effects turns out to be rather fine as the orbital separation increased to $a_f \approx 5R_*$ and not the $25R_*$ expected in conservative evolution for the observed final mass ratio. Further simulations are needed to determine whether the survival of the stellar core is a robust result valid for a wide range of initial mass ratios.

7. Astrophysical Implications

It would be premature to claim that the results of our simulation describe a process actually occurring in nature. However we would like to note two features of our results which, if confirmed by more extensive computations, could have profound implications for high energy astrophysics.

First, as noted in Section 1, the binary merger of a neutron star with a black hole is thought to be the most likely source of gamma-ray bursts. The very short duration of the accretion event, the lack of an accretion torus, and the presence of a substantial number of baryons along the axis of the binary – all observed in our simulation – would make this gamma-ray burst model untenable.

Second, the survival of a low mass stellar core in the binary raises interesting possibilities. A neutron star of the observed final mass 0.25 $M_\odot$ would be unstable to explosion. On the other hand, if the actually surviving stellar remnant were of sufficiently large mass, the neutron star would survive the first dynamical instability. Accretion episodes and the final destruction of the star would then follow, well separated in time from the first violent event.

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